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Prospects of Hybrid Renewable Energy-Based Power System: A Case Study, Post Analysis of Chipendeke Micro-Hydro, Zimbabwe

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ABSTRACT Fossil fuel-based energy sources are the major contributors to greenhouse gas (GHG) emission and thus the use of renewable energy (RE) is becoming the best alternative to cater for the increasing energy demand in both developing and developed nations. Chipendeke is a rural community in Zimbabwe, in which electricity demand is partially served by the only micro-hydro plant and hence, load shedding is a regular practice to keep essential services running. This study explored a suitable opportunity to identify a feasible system with different energy sources that can fulfill the current and projected future load demand of the community. A techno-economic feasibility study for a hybrid RE based power system (REPS) is examined considering various energy sources and cost functions. Six different system configurations have been designed with different sizing combinations to identify the most optimum solution for the locality considering techno-economic and environmental viability. The performance metrics considered to evaluate the best suitable model are; Net Present Cost (NPC), Cost of Energy (COE), Renewable Fraction (RF), excess energy and seasonal load variations. In-depth, sensitivity analyses have been performed to investigate the variations of the studied models with a little variation of input variables. Of the studied configurations, an off-grid hybrid Hydro/PV/DG/Battery system was found to be the most economically feasible compared to other configurations. This system had the lowest NPC and COE of $307,657 and $0.165/kWh respectively and the highest RF of 87.5%. The proposed hybrid system could apply to any other remote areas in the region and anywhere worldwide.

INDEX TERMS Chipendeke, Zimbabwe, hybrid renewable energy power systems, hydro, solar photovoltaic, battery, diesel generator.

I. INTRODUCTION

Energy particularly electrical energy is an essential part of modern days living, business and innovation. Access to electricity increases the potential to improve living standards, increase opportunity, improve health, productivity and reduces poverty [1]–[3]. It is now considered a basic human right for modern-day living, however, it is not equally experienced by all. More than half a billion people in Sub-Saharan Africa still do not have access to basic electrical energy

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services [4]. One example of such a nation is Zimbabwe, in which only 42% of its total population has access to electricity, with a rural electrification rate of only 13% [5], [6]. Fuelwood is still being commonly used in both urban and rural areas. In rural areas, they meet more than 80% of their energy requirements from fuelwood, whilst 15-30% of urban also rely on wood for cooking. Due to unsustainable wood harvesting and clearing of lands for agriculture, the country now faces fuelwood shortages and increased siltation of rivers thus affecting electricity generation from run-of-the-river hydro project, such as the case of Chipendeke, South of Mutare in Zimbabwe [7].

Zimbabwe's electricity power system relies heavily on coal (65%) and hydro (35%), which leaves the reliable power supply in danger during the recurring droughts. A total of 12 billion metric tons of good quality coal reserves are available in Zimbabwe, with calorific values of around 32 MJ/kg [8]. Zimbabwe has an installed electricity capacity of 1900 MW though on average only 492 MW is operational against a peak demand of 2200 MW [9]. Zimbabwe has suffered a rapid increase in energy demand mainly due to economic and population growth. Around 50% of Zimbabwe's population do not have access to basic electrical energy services, and 35% of the electricity currently being used are imported [10], [11]. Against this backdrop, there is an urgent need to explore all the possible generation technologies to increase the electrification rate. Inaccessibility to energy directly affects economic growth, food production, education, health, clean water, well-being, and social security.

Energy is considered as an enabler in achieving Sustainable Development Goals (SDGs) and it should be "affordable, reliable, sustainable and modern". One of the main goals of the SDGs is SDG7 to ensure energy access to all [12], [13]. In addition to lacking energy access in many countries, still, the major share of the national energy mix in most countries is by the use of fossil fuels which contribute to greenhouse gas (GHG) emissions. Moreover, the source of fossil fuel is limited and highly depending on this source may make the power system unreliable. Therefore, many countries strive deliberately to minimize the use of fossil fuels to attain sustainability in the energy sector [14]. Renewable energy (RE) sources, such as wind, solar PV and hydro on the other hand, are climate-friendly as they are free from GHG emissions and are abundant in nature. This has been proven by the increase in RE penetration into the energy mixes of many countries.

To address the energy crisis and SDGs goal, the Zimbabwe National Renewable Energy Policy (NREP) was published in March 2019 [6]. The goals and objectives of the NREP included the installation of 1100 MW of renewables by 2025 and 2100 MW of renewables by 2030. Renewables in this context referred to grid-connected solar PV, grid-connected wind, small hydro and bagasse. The policy reported the provision of tax and sale of power to third party incentives by the government and also reduce license fees for renewable energy projects. However, the policy does not outline any possible feed-in tariffs for RE resources which might still make investments unattractive. Additionally, the policy still does not mention any development of stand-alone micro-grids to electrify remote areas in which rural electrification rate is only 13% [6]. The NREP also reports that the Zimbabwean government will introduce mechanisms for funding RE systems as well as implement a RE technologies program that encourages independent power producers (IPPs) to invest in RE projects in Zimbabwe. Additionally, a fund is to be established by the Ministry of Energy to promote solar energy to address the electricity crisis. In line with the Government initiatives, this study aims to develop a hybrid renewable energy-based power systems (REPS) model to identify the techno-economic and environmental aspects of such implementations.

Recently, integration of RE sources in both grid-connected and off-grid systems was found to be the most efficient and attractive solution considering technical, economic and environmental perspectives, though there are potential limitations as generations from RE sources are variable and weather dependent. This issue becomes critical in rural areas in the absence of a central grid connection or the case of an off-grid system. Hence, hybrid power systems combining energy storage or diesel generator with RE sources in the form of microgrids (MGs) can make the systems more stable, reliable and efficient. It is evident from research that hybrid power systems with RE sources can be reliable, cost- economic, effective and more sustainable compared to either grid-connected or stand-alone generators utilising a single fossil fuel-based power source [15], [16]. Many countries around the world such as Australia [16], Bangladesh [17], India [18], Maldives [19], Saudi Arabia [20] and Zimbabwe [21] are currently doing in-depth research to deploy microgrid-based energy-efficient and reliable power systems for rural communities.

In literature, various methods of analysis, different RES combinations and different types of hybrid systems have been reported. Linear programming [23], excel-based [21], HOMER [24], [25], RETScreen [26], LINGO [27] and artificial intelligence [28], are frequently employed tools used in hybrid system analyses. Salisu *et al.* [29], highlighted the importance of a solar PV-wind-diesel-battery storage hybrid system in Nigeria and identified Giri village as the best location for their study. They used HOMER optimization tool to determine the Net Present Cost (NPC), Cost of Energy (COE) and Renewable Fraction (RF) of the proposed hybrid system [29]. Elkadeem *et al.*, modelled a system to determine the NPC, COE and reduction in carbon dioxide emissions for Sudan [30].

A modified crow search algorithm was employed in [31] for the optimisation of a hybrid solar photovoltaic (PV)-diesel-PHS (Pump Hydro Storage) system based on minimum operation costs. An excel-based model with various hybrid system configurations in the Turkish Republic of Northern Cyprus was investigated in [11]. In this study, a PV/Wind hybrid system incorporated with a Hydrogen Fuel Cell (HFC) and PHS was found to be cost-effective, efficient and viable. A detailed review on prospects of wind and solar power systems with PHS was performed and concluded that, for long term storage, PHS could be promising in the future [32].

Ganesan*et al.* [33] developed a model using Wind/PV/Diesel system and found that the operational cost of DG will be reduced with the use of RE resources. Fiedler *et al.* [34], studied 11 locations in Sweden and compared the energy cost of a hybrid PV-wind system to that of PV system alone. They also determined the effect of the size of the load on the proposed system. Table 1 summarises various hybrid REPS including system type, model or methodology employed and the outcome of those studies.

Research on energy harvesting from RE sources in Zimbabwe is still limited even though it lies in a sunny belt with daily average solar radiation of about 5.5 kWh/m^2 and a total of around 4000 hours per year of solar radiation [21]. Furthermore, the Chipendeke region, which is a case study location of this analysis, has average daily radiation of about 6 kWh/m^2 [22]. With this great potential of solar energy, a hybrid REPS with diesel backup may partially or fully support the deficit energy demand of Zimbabwe and particularly the need of Chipendeke.

II. CASE STUDY: CHIPENDEKE MICRO-HYDRO POWER SCHEME

This study considers a stand-alone power system that is already in operation in a rural settlement named Chipendeke in Zimbabwe to analyse and show that such systems have a significant influence on communities. Improvements for this system are then proposed based on energy demand with climate-friendly RE sources.

The Chipendeke with a catchment area of 9 villages, located 65 kilometres from the city of Mutare. The European Union donated $65000 towards Chipendeke micro-hydro project through the African Caribbean Pacific Energy Facility. The implementation of this project was led by Practical Action [54], which is an international organisation that uses smart technologies to eradicate poverty. The potential site for the micro-hydro power plant was identified along Chitoro River, which runs through Chipendeke. The plant can produce 25 kW of electricity and have a lifespan of 20 years. Initially, community members were against the idea of having a micro-hydro plant as they did not believe that they could operate and generate electricity.

The Chipendeke micro-hydro scheme is one of the pioneering micro-hydro schemes in Zimbabwe. The improvements that the community has made since its inception proved that it is a community that flourishes when it has the resources and would be a prime candidate for government funding as part of the country's rural electrification scheme. After the micro-hydro project, a rapid increase in energy demand was observed and a forecast of future demand growth was estimated in the Chipendeke community. Chipendeke has proven that it thrives with the use of electricity, with improvements at the health centre, education and businesses. This micro-hydro project became the income-generating source for many community members. However, due to change in climatic condition rainfall dropped and drought started as gradually the river lost its normal flow and, the micro-hydro project alone became incapable to meet the energy demand and the demand growth. Hence, implementation of a hybrid REPS could provide opportunities to extend the health services, education, business as well as to improve the social living standards.

A. IMPACT OF THE PROJECT

The project focused on the two main aspects of Chipendeke community's life, which are the domestic and social aspects. The clinic or health was the top priority, followed by the primary school, residential households and finally the businesses. Table 2 [55] summarises the benefits or the impacts that this project had on these four sectors.

B. OPERATION OF THE SYSTEM

There are two people in charge of operating the system. One person comes in the morning, and another is on standby in the evening for any faults or circuit tripping. Total eight people trained in the basic operation of the micro-hydro power plant, but for serious faults, ZESA is called in. The system is checked periodically, as well as every 3 hours. Data is collected in a counter book, recording the energy produced since 2010.

C. LOAD SHEDDING

Load shedding usually occurs a lot more between July to November as this is the driest time of the year and generation from micro-hydro power plant drops during this period. Households and businesses are the first to be switched off, with priority being given to the clinic. When the power generation drops to very low, the whole system shuts down and turned back on at night to provide electricity for lighting.

D. CONNECTION FEES AND TARIFFS

To keep the micro-hydro power system operational and to meet maintenance and operational cost the community members are required to pay energy tariffs as well as connection fees as set out in Table 3 [56]. The school and clinic pay the lowest tariffs as these locations provide a service to the community. Businesses pay the highest tariffs as they are a form of income-generating operation and this is also used to encourage business owners to use electricity more efficiently.

E. ISSUES AND FUTURE UPGRADES

Women in Chipendeke community greatly appreciate the addition of lighting facilities but have also expressed a desire for more amount of power generation for cooking [55]. Currently, they still rely on wood fuel for their cooking needs. Secondly, there is no backup power system available during times of the year when water levels are low. Moreover, the data recording system of the micro-hydro plant is very primitive and old, which is the critical information for the

TABLE 1. Summary of hybrid REPS in literature.

Ref	Location	System type	REPS technologies	Model	Research outcome	Performance metrics	Load forecasting
[35]	Algeria	Standalone	Solar PV-wind-PHS-Battery storage	MATLAB	In comparison to separate modes of storage, the hybrid PHS-battery storage system has 97.5% reliability, -COE 0.162€/kWh against 1.462€/kWh and 0.207€/kWh for only PHS and battery storage respectively.	COE and Loss of power supply probability (LPSP)	No
[36]	Bangladesh	Grid-connected and standalone	Solar PV-wind-battery	HOMER	The study investigated the techno-economic potentials of hybrid standalone and grid-connected wind and solar systems in different areas in Bangladesh namely; Rangpur, Magnama, Sitakunda, Kuakata and Dinajpur.	NPC, COE, RF and GHG emissions reductions	No
[37]	Cameroon	Standalone	Solar PV-hydro-diesel-battery storage	HOMER	The developed system was resilient to streamflow variations and economically feasible.	COE	No
[38]	China	Standalone	Hydro-solar PV	LINGO	The multi-objective optimization technique was able to solve conflicts between economical and reliable power supplies.	COE	No
[39]	Ecuador	Standalone	Solar PV-fuel cell -battery storage	HOMER	The COE of this modelled system was more than the average COE of Ecuador, hence the system was not economically feasible.	COE	No
[40]	Ethiopia	Standalone	Hydro-PV-wind	HOMER	The developed feasible system had the lowest COE of 0.16$/kWh.	COE	No
[41]	Ghana	Standalone	Soar PV-biodiesel-battery	HOMER	Prospects of hybrid energy system consisting of solar PV and biodiesel generators in meeting the electricity and domestic water needs of a remote community in Ghana has been investigated from which it was seen that the cost of deploying to a community of 100 households is estimated at $243,000 with an LCOE of $0.76/kWh.	LCOE	No
[42]	Hong Kong	Standalone	Solar-wind-PHS	Mathematical model	PHS was able to enable 100% energy autonomy in the remote island in Hong Kong.	LPSP and GHG emissions reductions	No
[43]	India	Standalone	Solar PV-wind-biodiesel-battery storage	HOMER	The proposed system proved to be economically feasible for sustainable electricity supply in Kordadu, India.	COE and NPC	No
[44]	Ukai, India	Grid-connected	Solar PV-hydro-diesel-bio generator-battery storage	HOMER	The proposed system had the lowest NPC and COE of $831,217 and $0.196/kWh respectively.	NPC and COE	No
[45]	Iran	Standalone	Soar PV-diesel-battery	HOMER	This study has evaluated the potentialities of renewable hybrid systems over fossil fuel-based systems with diesel generation. It was evident that the proposed system was cost-competitive.	NPC, LCOE and GHG emissions reductions	No
[46]	Malaysia	Grid-connected and Standalone	Hybrid PV-hydro-wind-battery	HOMER	Identified suitable locations in rural areas of Malaysia for hybrid renewable energy system. The Tioman Islands and Malaysian Borneo Islan has been selected as the most attractive regions for the PV/wind/hydro and solar/hydro system respectively.	NPC	No
[47]	Nigeria	Standalone	Soar PV-wind-diesel-battery/fuel cell	HOMER	Hybrid renewable energy-based power systems play an influential role to improve rural healthcare delivery considering technical, economical and environmental perspectives.	RF, NPC and COE	No
[48]	Nigeria	Standalone	Solar PV-hydro-wing-battery storage-diesel	HOMER	The system was feasible with a renewable energy fraction of 77.4%.	RF	No
[49]	Masirah Island, Oman	Islanded	Solar PV-wind-diesel	HOMER	The analysis aimed to design a system that minimises costs and pollution. The hybrid system comprising solar PV, wind and diesel generator was found as the optimal configuration which resulted in a 75% reduction in COE and 25% reduction in GHG emissions compared with the diesel generator only system that was utilised at Masirah Island	COE and GHG emissions reductions	No

TABLE 1. ***(Continued.)*** **Summary of hybrid REPS in literature.**

[50]	Rwanda	Standalone	Hydro-solar PV-battery storage	HOMER	The developed system was environmentally friendly due to less greenhouse gas emissions and it was also cost-effective		
[51]	Al-Jubail, Saudi Arabia	Standalone	Hybrid PV-wind-diesel-battery	HOMER	Renewable energy-based system is techno-economically feasible for the studied City. This 100% hybrid system will reduce more than 2800 ton of CO_2 equivalent gases per year.	GHG emissions reductions	No
[30]	Dongola, Sudan	Standalone	Solar PV-wind-diesel-battery	HOMER Pro	Solar-wind-diesel-battery developed an optimum system. The system had a minimum value of a COE of 0.387$/kWh and a 95% reduction in greenhouse gas emissions.	COE and GHG emissions reductions	No
[52]	United Arab Emirates	Standalone	Solar PV-diesel	HOMER	A dual-axis PV system was employed to meet 100% of the city's energy demands with an excess of 9.81% energy. Additionally, a greenhouse gas emission reduction of 69.6% was observed.	GHG emissions reductions	No
[21]	Gwanda, Zimbabwe	Standalone	PV-Wind	HOMER	A techno-economic evaluation of a standalone hybrid PV/wind system.	LCOE	No
[53]	Zimbabwe	Grid-connected	Solar PV-wind	Microsoft (MS) Excel	The levelised COE of Zimbabwe was less than the LCOE of the developed system, hence the system was not feasible. This was mainly because of the poor wind resources in Gwanda, Zimbabwe.	COE	Yes
Proposed Research	Chipendeke, Zimbabwe	Standalone	Solar PV-Hydro	HOMER	A techno-economic feasibility study for a hybrid REPS is investigated considering various energy sources and cost functions to identify the most suitable solution for Zimbabwe.	COE, NPC, RF, Excess Electricity	Yes

TABLE 2. **Impacts of the micro-hydro project in the Chipendeke community [55].**

Sector	Before the micro-hydro	After the micro-hydro
Chipendeke Rural Health Centre	• The clinic used lignified petroleum gas fridges to store medicines. • The candle lighting was dangerous, especially during the delivery of babies. • Only met 50% of its vaccination and immunisation targets.	• Improved lighting • Efficient storage of medicine and medical equipment. • The clinic meets 95% of its vaccination and immunisation targets. • Satellite television and phone charging facilities installed.
Chipendeke Primary School	• Unable to use electrical equipment such as printers and computers, with students and teachers having to travel 65km to the nearest city of Mutare to do so. • 9 teachers. • 300 students in 2009	• Established a computer learning centre by the German Embassy. • 16 teachers. • 640 students in 2014. • Running adult night classes and in 2015, 240 mature age students registered to sit for their Ordinary Level examinations
Business Centre	• Unable to sell fresh products like meat and fish. • Fewer shops and they only operated during the day for fewer hours.	• The community watched the 2010 Worldcup finals for the first time. • Refrigeration of fresh products • More shops and longer operating hours.
Residential Households	• No electrification. (Masimba Biriwasha 2017).	• 53 households connected with the possibility of increasing to 200.

regular maintenance, upgradation, lifespan estimation of the plant and for future planning activities.

The secretary-general of Chipendeke micro-hydropower scheme strongly believes that the micro-hydro plant needs to upgrade. The Chipendeke community has grown since the start of the micro-hydro, therefore power demand has increased [55]. There are plans to include a small cottage industry as well as carpentry, welding and peanut butter making machines within the community. Chipendeke committee also wants to supply electricity to surrounding villages and

TABLE 3. Chipendeke micro-hydro Scheme tariffs and connection fees [56].

Category	Tariff	Connection fee
Domestic household (shareholders)	16c/kWh	$US 30
Other residents	16c/kWh	$US70
Businesses	32c/kWh	$US 100
School and Clinic	10c/kWh	Free
Maintenance Levy for households, clinic and school	$3/month	
Maintenance Levy for businesses	$US 15	
Security guard allowance	$US 20	

are hoping to expand the system to 100 kW by making use of other renewable sources such as solar and biogas. They also hope to sell excess electricity to ZESA in the future [54].

F. SOLUTIONS FOR CHIPENDEKE

Chipendeke is a growing community that has embraced the use of RE sources. As the population grows and the electricity demand increases, there is a need for more generation capacity. The main issues identified for the system are:

- 6 kW generation deficit due to the El Nino drought which caused a reduction in the water levels of Chitoro river.
- The current system is not capable of addressing the cooking needs of the community. As a result of this, firewood is the main source of cooking energy, which plays a significant part in deforestation and air pollution.
- There is load shedding between July to November. These are the driest months of the year and there is currently no backup system to cater for the reduced water levels during this dry period.

Therefore, there is a significant scope of research to investigate the feasibility of developing a hybrid REPS, for Chipendeke which can address the current and expected extended demand for electricity and can be an example to other parts of Zimbabwe and beyond.

III. RESEARCH GAPS and CONTRIBUTIONS

Considering the needs of Chipendeke community as well as for Zimbabwe, this research aims to investigate the potentials of hybrid REPS including existing hydro for Chipendeke community with an emphasis on techno-economic and environmental benefits. Existing literature explored the potentialities of hybrid REPS taking into account local perspectives and other fundamental characteristics as shown in Table 1. Table 1 also demonstrated a comparative analysis of the proposed research with the existing researches. A few of the major research gaps are:

- From the reviewed literature, it was observed that there is a little or no research available that investigated the hybrid renewable energy system considering load growth or forecasted load data.
- REPS under Zimbabwe climatic condition were not covered in detail by the existing researches.
- Lack of researches that integrate continuous power generation from hydro with the variable PV generation.

To address the above research gaps, this study brings the following contributions as well as outcomes in the research domain:

- This study investigated the Zimbabwe power system and climatic conditions with forecasted or load growth for the hybrid REPS to fill the gap and explore the potential for Zimbabwe. It covers a rural Chipendeke community and data utilized were gathered through operational reports of Chipendeke micro-hydro scheme and from interviews with the residents.
- Coordinated operation of Chipendeke's micro-hydro together with solar PV, energy storage and diesel generator (DG) could not only help to reduce the energy crisis but also overcome the fluctuation problems that are associated with these renewable energy sources (RES).
- This is one typical study to be performed for Zimbabwe, hence it is of paramount importance to policymakers as it aligns with Vision 2030, in which the country hopes to increase the electrification rate and reduce greenhouse gas emissions.
- The outcome of this research will be a useful tool for power utilities and government bodies in planning for the deployment of hybrid REPS for rural communities.
- The proposed research method can be used in any remote or islanded areas to identify the techno-economic aspects for the deployment of hybrid REPS.

The rest of this paper is organised as follows; Section II presents the details of the case study. Section III presents the research gaps and contributions whilst Section IV outlines the employed methodology. Section V presents the results in order to identify the techno-economic and environmental feasibility of the proposed REPS while the discussions and the concluding remarks are presented in Section VI and Section VII respectively.

IV. METHODOLOGY

Hybrid REPS have been developed to support both the current and future predicted load demand of the Chipendeke community. Initially, a generic method is developed to estimate the current and future load demand of the community. A model is then developed using the Hybrid Optimization Model for Multiple Energy Resources (HOMER) [57] and optimisation analyses of the models are performed to select an optimum model for Chipendeke. The model performances are evaluated based on performance metrics such as; NPC, CoE and RF. Finally, sensitivity analyses are performed to study the effects of the optimum model with little variation of several input parameters. Figure 1 shows the step by step methodology while a detailed explanation for each is provided in the following subsections.

Different energy sources are considered in simulations to get an optimized system configuration. Six case scenarios

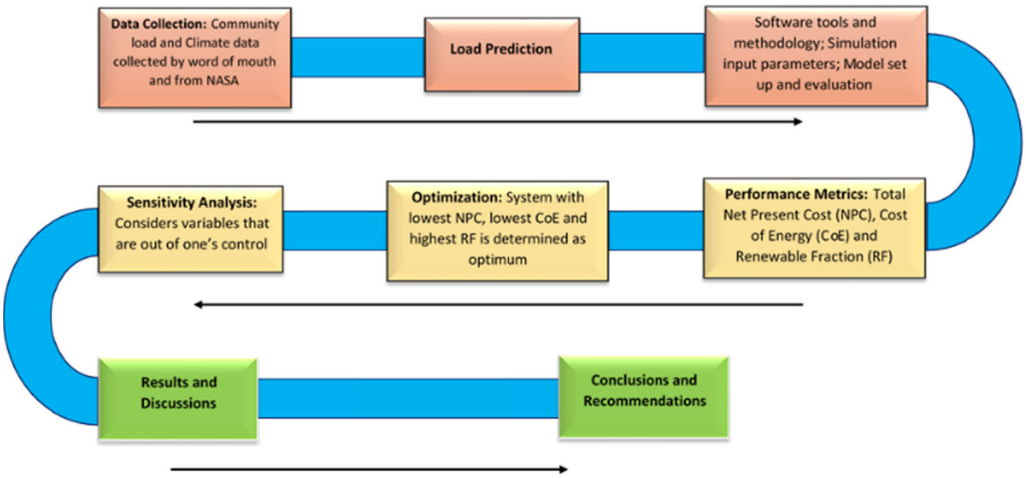

FIGURE 1. **Methodology flowchart.**

were studied using HOMER simulation software and compared their performances based on performance metrics. Scenarios are:

- Case-1: Base Case: Hydro-Only
- Case-2: Hydro, Solar PV and Battery (Hydro/PV/Battery)
- Case-3: Hydro, Solar PV, Diesel Generator (DG) (Hydro/PV//DG)
- Case-4: Hydro, Solar PV, DG and Battery (Hydro/PV/DG/Battery)
- Case-5: Hydro, DG and Battery (Hydro/DG/Battery)
- Case-6: Hydro and DG (Hydro/DG)

A. COMMUNITY LOAD DEMAND

In collaboration with Hivos Project Manager, a load profile of Chipendeke community was determined. Various assumptions were made for the community and hours of working of appliances. For the 200 households at Chipendeke, it is assumed that each house has 4 rooms, with one bulb in each room for lighting.

1) LOAD PROFILE

In collaboration with Hivos project manager, a load profile of Chipendeke community was determined. Various assumptions were made for the community and hours of working of appliances. For the 200 households at Chipendeke, it is assumed that each house has 4 rooms, with one bulb in each room for lighting.

2) CURRENT LOAD PROFILE

Based on the preliminary analysis it was found that Chipendeke currently has a peak demand of approximately 15 kW which occurs at 8 am with higher levels of electricity demand during the morning and evening periods as shown in Figure 2. This load profile does not include the use of cooking stoves, as this is not currently supported by a micro-hydro scheme. To determine a suitable hybrid system for Chipendeke, several estimations were made based on information provided by Mr. Mapfumo, as well as collected information from the facilities located in the community. Table 4 shows the four critical locations that require power to be supplied and details of the appliances listed that have been considered. These assumptions were made based on the operational hours of various appliances as shown in Table 5.

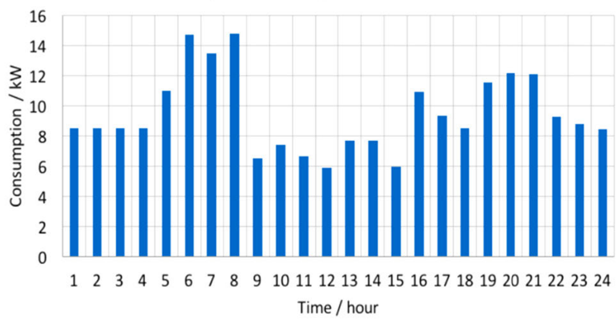

FIGURE 2. **Current load profile of Chipendeke.**

To develop a load profile, the operating hours of each of these appliances are required. Figure 3 and Figure 4 show a minimum approximation of the power consumption of each appliance and its time of operation for an average weekday and weekend use based on the analytical model in [58]. The various assumptions made in Table 6 as well as household cooking stove load also considered as represented in Figure 3 and Figure 4.

3) PREDICTED LOAD PROFILE

According to Hivos project manager, the community of Chipendeke has grown by 7% within the last 8 years. As there is no published statistical record about the population growth in Chipendeke, this growth is estimated based on the word of mouth from the community leaders.

TABLE 4. Chipendeke community load requirements.

Location	Load	Maximum quantity	Nominal power (W)	Total power (W)
Health centre	Fluorescent lights	22	40	880
	Medical refrigerator	2	150	300
	Kitchen refrigerator	1	300	300
	Sterilizer	1	3500	3500
	Geyser	1	4800	4800
	Heating facility	8	580	4640
	Kettle	1	750	750
	TV	1	250	250
Business centre	Fluorescent lights	12	40	480
	Filament lights	6	25	150
	Freezer	2	450	900
	Old refrigerator	6	300	1800
	Radio	3	100	300
	TV	1	250	250
Primary school	Phone charger	11	4	44
	Computers	14	70	1050
	Filament lights	31	25	775
	Refridgerator	1	150	150
	Kettle	1	750	750
Households	Filament lights	800	25	20000
	TV	10	250	2500
	Phone charger	400	4	1600
	Stove	10	2500	25000

TABLE 5. Load operating hour assumptions.

Location	Weekday assumptions	Weekend assumptions
Health centre	• 2 fluorescent lights are on at any given moment • 11 fluorescent lights are on from 7 am – 9 am and from 7 pm – 10 pm • 6 fluorescent lights are on from 6 pm – 7 pm • All heating facilities are used from 12 am – 5 am • 4 heating facilities are used from 6 am – 8 am and from 11 pm – 12 am	
Business centre	• 4 fluorescent lights are on from 6 pm – 8 pm • 2 fluorescent lights are on from 8 pm – 11 pm • 3 filament lights are on from 6 pm – 11 pm • 1 filament light is on from 8 pm – 11 pm	
Primary School	• From 7 pm – 10 pm, two classrooms are used for night classes. Each classroom has 2 filament lights.	• Only the refrigerator is in operation.
Households	• 200 filament lights are on from 5 am – 6 am, 7 am – 8 am, 6 pm – 7 pm, 10 pm – 11 pm. • 400 filament lights are on from 6 am – 7 am, 7 pm – 9 pm. • 80 filament lights are on from 8 am – 9 am. • 5 TVs are on from 1 pm – 2 pm. • 7 TVs are on from 5 pm – 7 pm. • 10 TVs are on from 8 pm – 10 pm. • 3 stoves are on between 6 am – 7 am, 5 pm – 7 pm. • 4 stoves are on at a time between 12 pm – 1 pm	• 200 filament lights are on from 7 am – 8 am, 6 pm – 7 pm, 10 pm – 11 pm. • 400 filament lights are on from 6 am – 7 am, 7 pm – 9 pm. • 80 filament lights are on from 8 am – 9 am. • 5 TVs are on from 12 pm – 2 pm. • 10 TVs are on from 5 pm – 10 pm. • 4 stoves are on between 12 pm – 1 pm.

To cater for the future load growth of the community, it is assumed that within the 25-year lifespan of the project, the community will grow by 15%. Therefore, an updated load profile is prepared based on the load profile shown in Figure 3 and Figure 4 and considering 15% load growth as shown in Figure 5. This is used to determine the hybrid REPS for the Chipendeke community, considering variations of weekday and weekend load demand. The main difference between a weekend and a weekday is the lower electricity demand from the primary school during weekends. The peak demand for both a weekday and a weekend is 32 kW which occurs at 6 am, with a weekday average demand of 16.84kW and a weekend average demand of 16 kW. Monthly load profile considered for the study of the Chipendeke community is shown in Figure 6. A day to day random variability of 2% has been considered for load due to the seasonal variations as well as the changes of usage by the consumers in the community. HOMER changes each day's load profile by this amount that the load retains the same shape with a variation of its magnitude, either scaled up or down.

B. CLIMATE DATA

1) RAINFALL

The Chipendeke micro-hydro project depends on the water flow in Chitoro River. A river water speed of 75L/s has been used for simulation in this study considering the climate/seasonal changes and error rate though the system was designed to provide 100L/s in both the dry and wet seasons. As information regarding the seasonal changes for this river was not available, monthly precipitation data of the surrounding areas of Rusape [59], Wedza [60], and Old Mutare [61] is considered. These areas are the closest locations to Chipendeke for which rainfall data was obtainable and used to determine the average monthly rainfall for the area.

This rainfall data was then compared to the historical data repository managed by NASA [62]. Table 6 was used to determine the average rainfall for Chipendeke as it considers all three closest areas to it. It is assumed that the speed of the river will have monthly variations that are in proportion to the amount of precipitation that occurs. As observed in Table 6, the speed of the river remains at 75 L/s from May to September which is the dry season of the year, then higher speeds

<table>
<tr><td></td><td>Time (hour)</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td></tr>
<tr><td rowspan="10">Health Centre</td><td>Medical Refrigerator</td><td colspan="24">300</td></tr>
<tr><td>Kitchen Refrigerator</td><td colspan="24">350</td></tr>
<tr><td>Fluorescent Lights</td><td colspan="6">80</td><td colspan="3">440</td><td colspan="8">80</td><td>260</td><td colspan="4">440</td><td colspan="2">80</td></tr>
<tr><td>Sterilization Equipment</td><td colspan="5"></td><td colspan="3">3500</td><td colspan="7"></td><td colspan="2">3500</td><td colspan="7"></td></tr>
<tr><td>Kettle</td><td colspan="6"></td><td colspan="2">750</td><td></td><td colspan="2">750</td><td colspan="4"></td><td>750</td><td colspan="8"></td></tr>
<tr><td>TV</td><td colspan="7"></td><td colspan="2">250</td><td colspan="3"></td><td colspan="2">250</td><td colspan="4"></td><td colspan="3">250</td><td colspan="3"></td></tr>
<tr><td>Phone Charger</td><td colspan="6">44</td><td colspan="7"></td><td colspan="3">44</td><td colspan="8"></td></tr>
<tr><td>Heating Facilities</td><td colspan="5">4640</td><td colspan="3">2320</td><td colspan="14"></td><td>2320</td><td>4640</td></tr>
<tr><td>Geyser</td><td colspan="7"></td><td colspan="4">4800</td><td colspan="3"></td><td colspan="3">4800</td><td colspan="7"></td></tr>
<tr><td></td><td colspan="24"></td></tr>
<tr><td rowspan="5">Primary School</td><td>Computers</td><td colspan="7"></td><td colspan="9">1050</td><td colspan="8"></td></tr>
<tr><td>Filament lights</td><td colspan="7"></td><td colspan="9">775</td><td colspan="2"></td><td colspan="3">100</td><td colspan="3"></td></tr>
<tr><td>Refrigerator</td><td colspan="24">350</td></tr>
<tr><td>Kettle</td><td colspan="7"></td><td>750</td><td></td><td>750</td><td colspan="5"></td><td>750</td><td colspan="8"></td></tr>
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<tr><td rowspan="7">Business Centre</td><td>Fluorescent Lights</td><td colspan="17"></td><td colspan="2">140</td><td colspan="4">80</td><td></td></tr>
<tr><td>Filament Lights</td><td colspan="17"></td><td colspan="2">75</td><td colspan="4">25</td><td></td></tr>
<tr><td>Freezer</td><td colspan="24">900</td></tr>
<tr><td>Old Refrigerator</td><td colspan="24">1800</td></tr>
<tr><td>Radio</td><td colspan="8"></td><td colspan="9">300</td><td colspan="3">100</td><td colspan="4"></td></tr>
<tr><td>TV</td><td colspan="6"></td><td colspan="2">250</td><td colspan="4"></td><td colspan="2">250</td><td colspan="10"></td></tr>
<tr><td></td><td colspan="24"></td></tr>
<tr><td rowspan="5">Households</td><td>Filament Lights</td><td colspan="4"></td><td>5000</td><td>10000</td><td>5000</td><td>2000</td><td colspan="9"></td><td>5000</td><td colspan="3">10000</td><td colspan="2">5000</td><td></td></tr>
<tr><td>TV</td><td colspan="12"></td><td colspan="2">1250</td><td colspan="2"></td><td colspan="3">1750</td><td colspan="3">2500</td><td colspan="2"></td></tr>
<tr><td>2 Plate Stove</td><td colspan="5"></td><td colspan="2">7500</td><td colspan="4"></td><td colspan="2">10000</td><td colspan="3"></td><td colspan="3">7500</td><td colspan="5"></td></tr>
<tr><td>Phone Charger</td><td colspan="6">44</td><td colspan="15"></td><td colspan="3">44</td></tr>
<tr><td></td><td colspan="24"></td></tr>
<tr><td></td><td>TOTAL (kW)</td><td>8.51</td><td>8.51</td><td>8.51</td><td>8.51</td><td>13.51</td><td>27.19</td><td>23.46</td><td>20.59</td><td>11.32</td><td>12.21</td><td>11.46</td><td>15.91</td><td>17.66</td><td>7.70</td><td>10.75</td><td>15.75</td><td>21.63</td><td>18.53</td><td>24.06</td><td>17.20</td><td>17.10</td><td>11.79</td><td>11.25</td><td>8.46</td></tr>
</table>

FIGURE 3. Weekday load requirements.

<table>
<tr><td></td><td>Time (hour)</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td></tr>
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<tr><td>Geyser</td><td colspan="7"></td><td colspan="4">4800</td><td colspan="3"></td><td colspan="3">4800</td><td colspan="7"></td></tr>
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<tr><td rowspan="7">Business Centre</td><td>Fluorescent Lights</td><td colspan="17"></td><td>140</td><td colspan="5">80</td><td></td></tr>
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<tr><td>Freezer</td><td colspan="24">900</td></tr>
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<tr><td></td><td>TOTAL (kW)</td><td>8.51</td><td>8.51</td><td>8.51</td><td>8.51</td><td>8.51</td><td>27.19</td><td>23.21</td><td>17.76</td><td>9.39</td><td>9.53</td><td>9.53</td><td>15.23</td><td>15.73</td><td>5.77</td><td>8.82</td><td>13.07</td><td>22.28</td><td>19.28</td><td>24.60</td><td>17.10</td><td>17.10</td><td>11.89</td><td>11.25</td><td>8.46</td></tr>
</table>

FIGURE 4. Weekend load requirements.

are observed during the rainy season from November to February.

2) RENEWABLE RESOURCE SELECTION

Chipendeke has a high average solar radiation of around 6 kWh/m^2/day which makes it a good candidate for the use of solar PV, whilst the average wind speed of the area is only 4.65 m/s. The minimum speed at which a wind turbine begins to produce power, or the cut-in speed is approximately 3 m/s [21], and with Chipendeke average wind speed very close to this, therefore wind is not considered as a potential source for the REPS.

3) SOLAR RESOURCE

Hourly solar radiation data for Chipendeke are collected from the historical data repository managed by NASA [63]. The daily radiation and the clearness index of Chipendeke are shown in Figure 7. Chipendeke receives average daily radiation of 6 kWh/m^2/day, with the lowest amount of radiation occurring in June.

C. MODEL EVALUATION USING HOMER

The model was developed in HOMER based on the current micro-hydro scheme already at Chipendeke and included additional RE sources available in the area. The model is

TABLE 6. Rainfall in millimetre (mm) and litre (L) for three adjacent areas of Chipendeke [59]–[61].

Month of the Year	J	F	M	A	M	J	J	A	S	O	N	D
Rusape (mm)	166	149	81	40	13	7	4	5	9	41	106	168
Wedza (mm)	157	152	77	48	13	8	3	5	10	43	97	178
Old Mutare (mm)	177	141	90	25	12	9	6	7	10	34	98	163
Avergae Rainfall (mm)	166.7	147.3	82.7	37.7	12.7	8.0	4.3	5.7	9.7	39.3	100.3	169.7
Avergae Rainfall (L)	4.6	3.2	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.1	1.0	8.9
Estimated Chittoro River Speed (L/S)	79.6	78.2	75.6	75.1	75.0	75.0	75.0	75.0	75.0	75.1	76.0	79.9

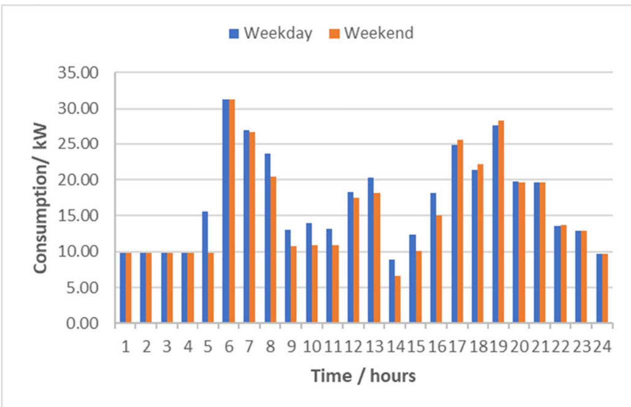


FIGURE 5. Predicted load profile for Chipendeke.

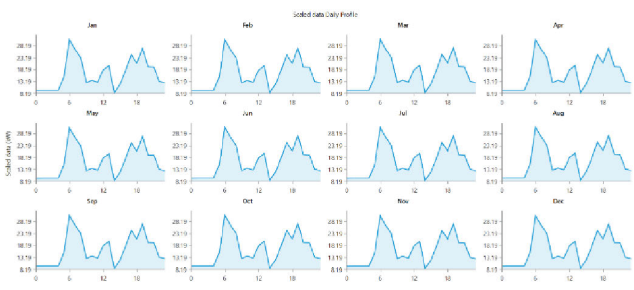


FIGURE 6. Predicted monthly load profile for Chipendeke.

optimization based on the considered energy resources and cost of resources. Furthermore, sensitivity analysis is done to evaluate economic feasibility with various technology options. To estimate the most feasible system configuration the three core capabilities of HOMER, simulation, optimization and sensitivity analysis [57] are executed.

For this study, the three main performance metrics that were taken into consideration are the NPC, COE and RF or contribution from renewable resources. Various resources are considered in six different cases and hybrid power systems are compared and evaluated based on these metrics. The NPC is the present value of all the costs that the entire system incurs throughout the project lifetime, minus the present

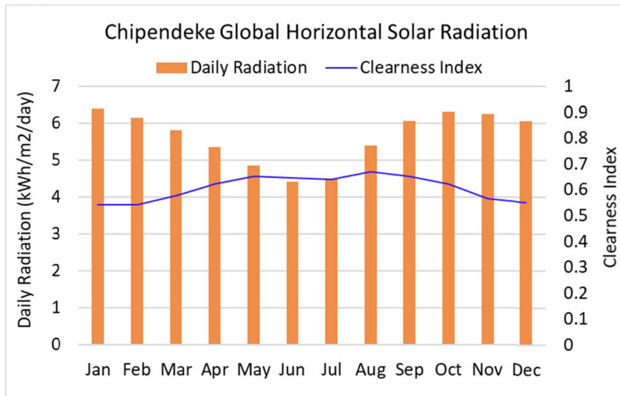


FIGURE 7. Global horizontal radiation and clearness index [63].

value of all the revenue it earns over its lifetime [57]. To determine whether or not to continue with a project, the economic or financial feasibility is a very important parameter to consider for this decision. Traditionally when determining the economic feasibility of energy systems, the levelized cost of electricity (COE) is one of the most important parameters to consider as it is the generated electricity cost by the system. The mismatching effect between the demand and generation was incorporated in the analyses by utilizing the demand met by the system, not the energy generated [57]. Additionally, as the RES is unable to meet 100 per cent of the demand, the deficit will be acquired from a diesel generator at the local grid tariff (GT), and this will affect the COE of the system. The portion of energy that is from a renewable power source that is delivered to the load is referred to as the RF. A high RF value means that the system is making more use of renewable energy [59].

A hybrid REPS, is a combination of RE sources, a storage battery and DG with a specific dispatch strategy. A set of rules to control the operation of the energy sources and to charge and discharge the battery under different circumstances are called dispatch strategies. Several dispatch strategies for hybrid REPS are discussed in [30], [31]. However, in this study, only cycle charging (CC) and load following (LF) dispatch strategies are considered [11]. In the CC strategy, the prime role of the generators is to serve the primary load. Excess generation after meeting the primary load is used to charge the battery bank. Only primary load (and operating reserve) are served by the LF strategy. RE sources are responsible to charge the battery bank. Diesel generators are not required to run just to support grid frequency and voltage hence, a diesel-off operation is enabled in this study. The inverters used in the hybrid REPS are expected to have grid-forming capabilities.

D. SENSITIVITY ANALYSIS

A sensitivity analysis considers outlines how changes in variables in an extended range can affect system performance. The model has been simulated and the considered sensitivity variables are local load, solar irradiance, cost of PV, cost of the battery, hydro turbine efficiency, diesel price, nominal discount rate and inflation rate. The model has been identified the NPC of the most optimum system with the variations of the sensitivity variables.

E. HYBRID SYSTEM COMPONENTS

To carry out the economic analysis of the system, several variables were defined in HOMER model. These variables include the capital costs, operation, maintenance and replacement costs and project lifetime. This technical information can be found in Table 7. It is important to note that for this project, the lifetime of the existing micro-hydro scheme has been set to 12 years. This is because the average lifetime of this type of hydro system was 20 years and the micro-hydro scheme at Chipendeke has already been in operation for 8 years. A typical snapshot of the studied REPS is shown in Figure 8.

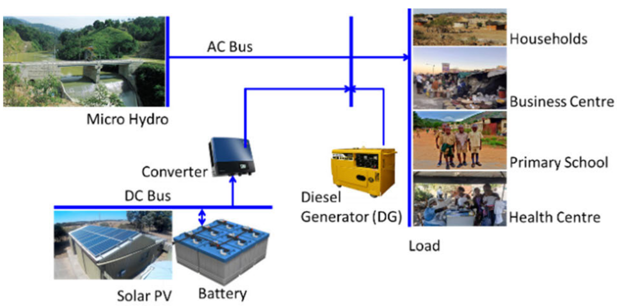


FIGURE 8. A typical snapshot of the studied REPS.

TABLE 7. Technical data and study assumptions.

Description	Value/Information
Hydro	
Initial Capital Cost	$0
Replacement	$100,000
O&M	$2000/year
Lifetime	12 years
Efficiency	75%
Pipe Head Loss	15%
PV	
Initial Capital Cost	$1500/kW
Replacement Cost	$1000/kW
Operation and Maintenance	$10/year
Lifetime	25 years
Diesel Generator	
Minimum Load Ratio	25%
Initial Capital Cost	$800/kW
Replacement Cost	$600/kW
Operation and Maintenance	$0.030/hour
Lifetime	15000 hours
Diesel Price	$1.30/L
Battery	
Name	Generic 1 kWh Lead Acid
Nominal Voltage	12V
Nominal Capacity	1 kWh
Initial Capital Cost	$300
Replacement	$300
Lifetime	2 years
Inverter	
Initial Capital Cost	$300/kW
Replacement Cost	$300/kW
Operation and Maintenance	0
Lifetime	20 years
Constraints	
Maximum annual capacity shortage	0%
Operating Reserve	
As a per cent of Hourly Load	10%
As a per cent of Solar power output	10%
Economics	
Nominal Discount Rate	8%
Expected Inflation Rate	2%
Project Lifetime	25 years

V. RESULTS AND ANALYSIS

A. OPTIMIZATION ANALYSIS

1) CASE-1: BASE CASE SCENARIO–HYDRO ONLY

From the preliminary analysis, it is evident that the existing hydro plant is not enough to meet the current community load demand. The major crisis is in the drought season. The simulation results of the Case-1 or Base Case scenario also provides similar findings. A hydro-only system can meet community load demand of only 164 kWh/day with the hydro efficiency of 75% as shown in Figure 9, which is far lower than the communities current energy demand. Figure 9 also shows the power generation options of other case scenarios and it is seen that Hydro/PV/DG/Battery system is the most suitable when the average load is more than 310 kWh/day which is the current demand of the community.

Figure 10 shows the power generation from hydropower throughout the day from which it is observed that there is less generation during the middle of the year when there is a low

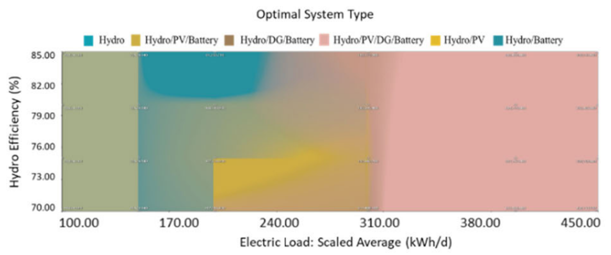


FIGURE 9. Electricity generation from hydro with the variations of turbine efficiency.

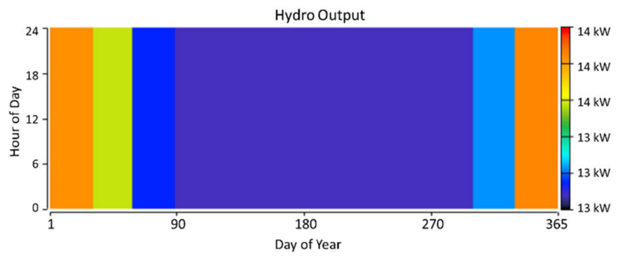


FIGURE 10. Power output from hydro throughout the year.

amount of rainfall. The hydro system produces its peak power at the end and beginning of the year, due to the increased water flow in the river.

2) CASE STUDY ANALYSIS

As the only existing hydro plant is not enough to meet the current and future load demand of Chipendeke community, this study explores possible generation options to meet communities current and future load demand. Five more case scenarios were investigated by integrating suitable RE generation technologies to identify the most suitable option based on techno-economic and environmental perspectives. Optimal system performance and sensitivity analyses have been carried out using HOMER to evaluate the performances of Hydro/PV/Battery, Hydro/PV/DG, Hydro/PV/DG/Battery, Hydro/DG/Battery and Hydro/DG systems.

It is found that the Hydro/PV/DG/Battery system (Case-4) is the most optimum based on the considered performance metrics compared to the other studied systems cases. The best-optimised model comprised a 25-kW hydro, 14.0 kW PV, 10 kW Genset, 36 batteries at 12V and 14.1 kW inverter to support the load of 144,450 kWh/yr.

In Case-4 a Hydro/PV/DG/Battery system, NPC, COE and RF are $307,658, $0.165/kWh and 87.5% respectively, while in Case-6 a Hydro/DG system, NPC, COE and RF are $451, 652, $0.242/kWh and 70.4% respectively. The cumulative nominal cash flow of the Hydro/PV/DG/Battery, the lowest cost system and the Hydro/DG, the highest cost system is shown in Figure 11. The simple payback and discounted payback period of the optimized Case-4 or Hydro/PV/DG/Battery system are 2.33 year and 2.44 year respectively.

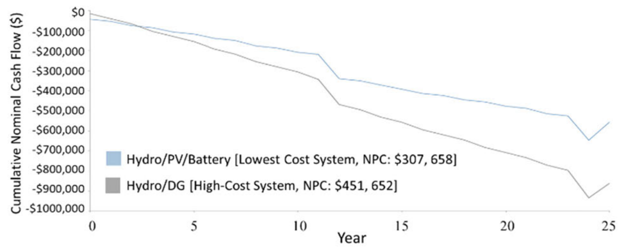


FIGURE 11. Cumulative nominal cash flow of the Hydro/PV/DG/Battery and the Hydro/DG system.

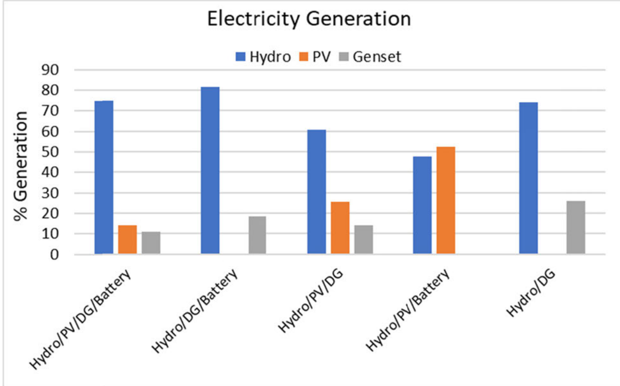
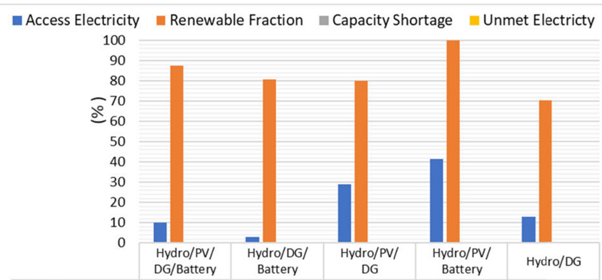


FIGURE 12. Electricity generation from different sources for the studied systems.

Figure 12 shows the electricity generation from different energy sources for the studied five cases (Case 2-6). The optimised case is Case-4 that includes Hydro/PV/DG/Battery system, where hydro generates a maximum of 75% of the total generated electricity while PV generates 14% as shown in Figure 12. The remaining 11% is generated by the diesel generator. In Case-2, PV generates the maximum electricity of 52.5% in the Hydro/PV/Battery system with the sacrifice of the highest NPC due to the increased use of batteries to store energy from PV during daytime and use this stored energy at night.



	Hydro/PV/ DG/Battery	Hydro/DG/ Battery	Hydro/PV/ DG	Hydro/PV/ Battery	Hydro/DG
Access Electricity	10.1	2.89	28.9	41.6	13
Renewable Fraction	87.5	80.7	80.2	100	70.4
Capacity Shortage	0.0839	0.0005	0.0022	0.0989	0.0389
Unmet Electricty	0.0001	0	0	0.0571	0

FIGURE 13. Renewable fraction, access electricity and capacity shortage of the studied systems.

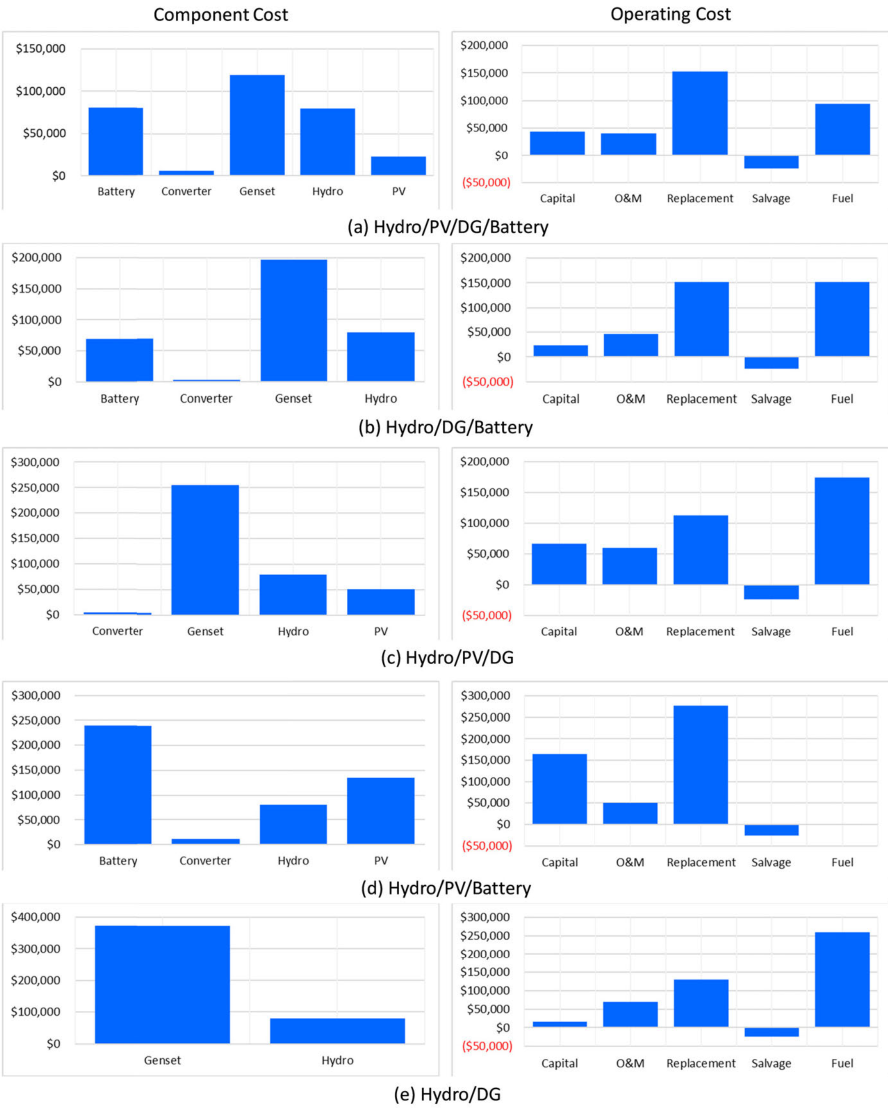


FIGURE 14. **Component- and Type-wise costs for the five studied systems.**

From Figure 13 it is seen that Case-2 or Hydro/PV/Battery system is the only system that generates 100% electricity from RE sources while it has the maximum of 41.6% excess electricity, as there is surplus electricity from PV due to high generation. Hence, it is evident that 100% of RE-based generation is possible for the Chipendeke community with the sacrifice of costs. On the other hand, the renewable fraction and the excess electricity for the optimised system, i.e., Case-4 are 87.5% and 10.1% respectively. From Figure 13, it is also seen that the capacity shortage and unmet electric load are negligible for all the studied cases, hence, it can be stated that all the studied cases can meet the load demand of the community.

Figure 14 shows the NPC of the studied cases from where it is observed that the majority of the costs are for the DG and the Battery. The micro-hydro scheme has not been included in the capital costs as it is a system that is already in place. However, the micro-hydro has been in operation for 8 years, with a life span of 20 years, therefore, it needs replacement cost after another 12 years into the operation and the hydro turbine replacement cost is fixed for all the studied cases. At the same time, in cost type, it is seen that the replacement cost is the highest for most of the studied cases throughout the project lifetime as there is a need to replace hydro turbine and batteries. Another significant cost is the fuel cost as fuel is needed to run Genset. Fuel cost is the lowest in the optimised Hydro/PV/DG/Battery system while it is the highest in the Hydro/DG system as DG contributed 25.8% of the total electricity in this case.

One of the goals of the study is to increase RE penetration to reduce greenhouse gas emissions for a sustainable and climate-friendly power system for the future. Table 8

TABLE 8. Comparison of emission parameters for the five studied cases.

Emissions Parameters	Hydro/PV/DG/Battery	Hydro/DG/Battery	Hydro/PV/DG	Hydro/PV/Battery	Hydro/DG
Carbon Dioxide (kg/yr)	14,766	23,634	27,202	0	40,369
Carbon Monoxide (kg/yr)	92.2	148	170	0	252
Unburned Hydrocarbons (kg/yr)	4.06	6.5	7.48	0	11.1
Particulate Matter (kg/yr)	0.553	0.885	1.02	0	1.51
Sulfur Dioxide (kg/yr)	36.2	57.9	66.6	0	98.8
Nitrogen Oxides (kg/yr)	86.6	139	160	0	237

shows that the Hydro/PV/Battery system has no emissions as it is a 100% RE-based system although it is the costliest system. From Table 8, it is evident that the optimised Hydro/PV/DG/Battery system has less emissions compared to the Hybrid/DG/Battery, Hydro/PV/DG and Hydro/DG systems.

3) OPTIMUM SYSTEM FOR CHIPENDEKE

From the case study analyses, it is observed that Case-4 or Hydro/PV/DG/Battery system has been selected as the most optimum system considering techno-economic and environmental perspectives. Figure 15 describes the power output of the optimised system from different energy sources throughout the year. The middle of the year is when there is the lowest amount of rainfall and clear skies, allowing the PV system and the DG to deliver the remaining power. The rainy season occurs at the end and beginning of the year and this is when hydro has a higher generation while DG requires its least. DG contributed more from April to August when the generation from hydro and PV is comparatively less.

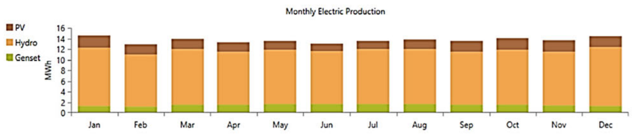


FIGURE 15. Monthly electricity production from different sources for the optimised system.

Figure 16 represents the capital, operating, replacement, resource and salvage costs for 25 years lifespan of the project for individual components as well as the total NPC of the optimised system. The total NPC of the entire system was found to be $307,657, with the capital, replacement and resource costs of $44,039 and $152,545 and $94,795 respectively, where the replacement cost is the highest. A significant cost is also required for fuel to run the Genset which is shown as resource costs.

The time series analysis takes a closer look at the generation sources at certain periods throughout the year. During the winter period as shown in Figure 17, the load is mainly supported by the hydro system, complemented using solar PV. However, in the early morning during peak demand with less PV generation hydro and DG fulfill the load demand. The excess electricity during day time is stored in the battery. During the night time, power from the stored batteries is

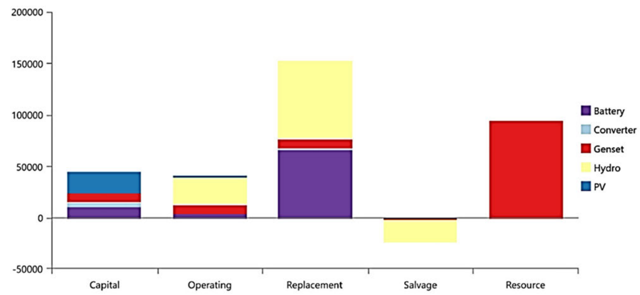


FIGURE 16. Cost summary of the optimised system.

supplied to the load via the inverter, as well as from the micro-hydro. During the summer period as shown in Figure 18, there is a slightly higher amount of output power from the hydro system due to increased rainfall. The generator is in operation during early morning and night time.

B. SENSITIVITY ANALYSIS

From the sensitivity analysis, the models were analysed to explore the characteristics of the studied cases with little variations of the input parameters. From Figure 19 it can be stated that with the increase of solar irradiation the COE of the optimised system is decreasing which indicates that energy generation from PV is comparatively cheaper compared to other considered sources. Figure 19 also shows that renewable fraction has increased with the increase in solar irradiation. From Figure 20, it is seen that with the increase of load demand the total NPC increases as the optimised system need to generate more electricity to meet the consumer demand. Annual electricity production also needs to increase to meet the increased load demand.

Finally, the model identifies the variability of its performance due to the changes of key variables as uncertainties make difficulties for the designer or utilities in implementing hybrid REPS system in the future. For example, due to technological growth, there will be significant changes in PV price with time which should be considered in making a good design decision. Again, inflation or nominal rate may change with time. Moreover, the equipment costs may vary with time, places, manufacturer and country of origin, which also need to be considered in designing a hybrid REPS system. In this study, eight key variables; electric load, the efficiency of hydro, diesel fuel price, nominal discount rate, inflation

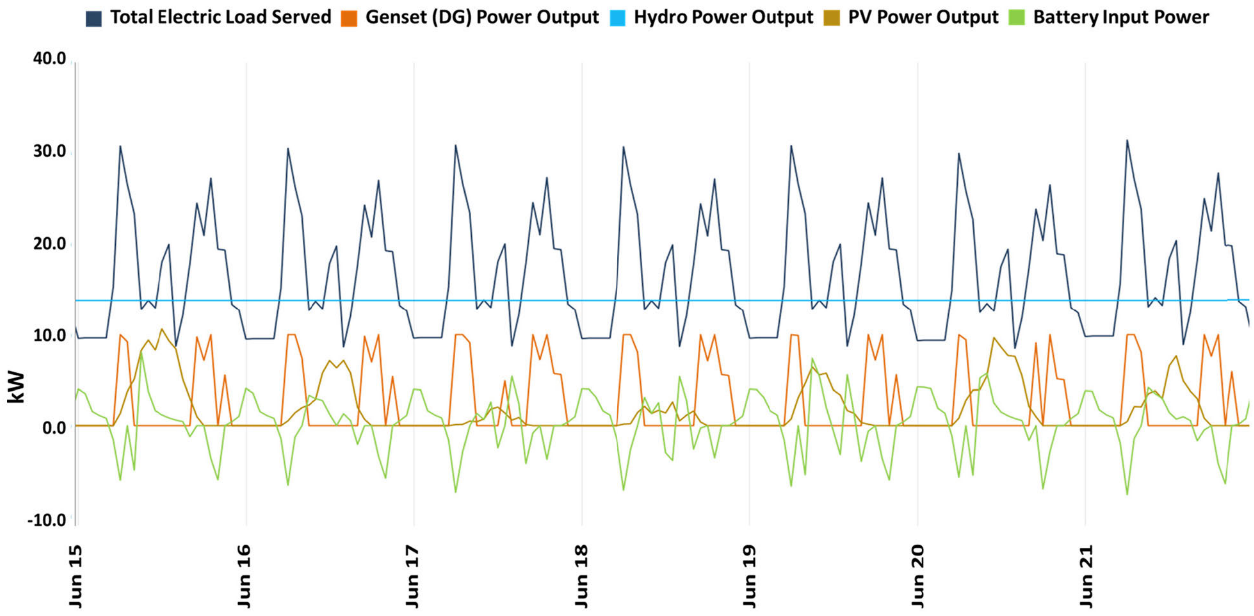


FIGURE 17. Energy generation from different sources during a week in the winter season.

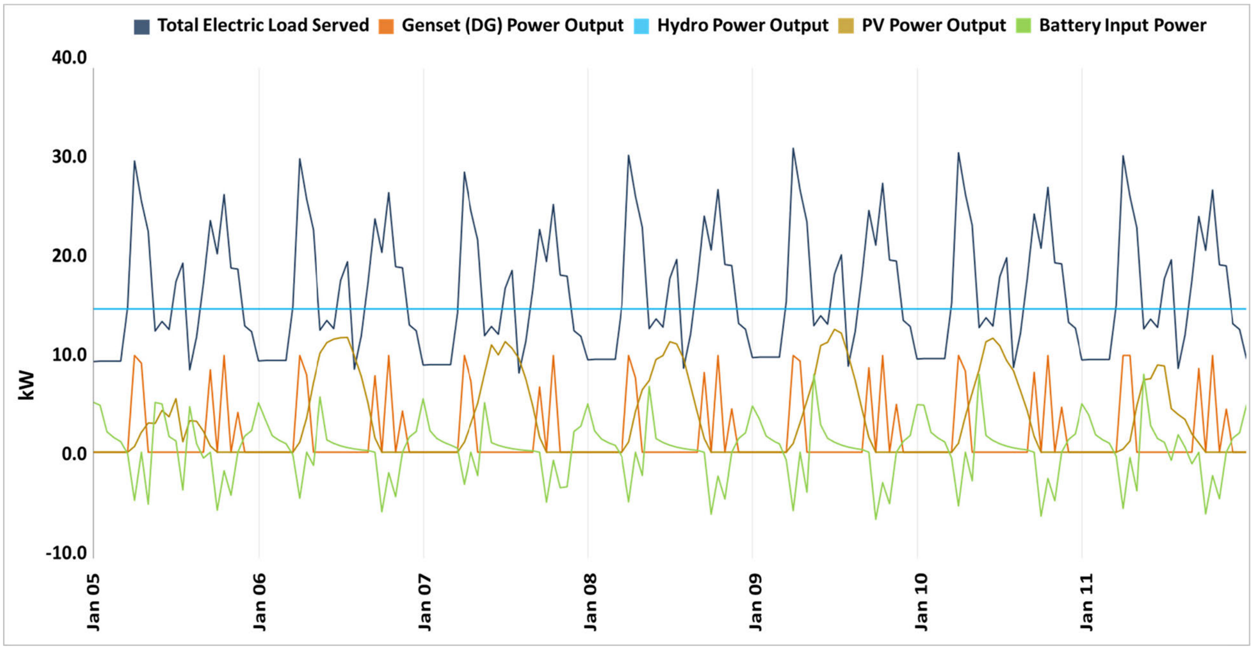


FIGURE 18. Energy generation from different sources during a week in the winter season.

rate, solar irradiation, PV capital cost and battery capital cost had been considered to explore the variability of the proposed optimised system with the variation of these variables. This will help the designer or decision-maker to identify the effectiveness of the system with the changes of these input parameters regarding performance, reliability, variability and robustness. Five manifold values ranging from 30% below to 30% above to the best estimate were considered for each of the key variables. Figure 21 demonstrated the changes of NPC as well as the sensitivity with the changes of the key variables from lower range to upper range. From Figure 21, it is seen that the NPC is the most sensitive with the changes of electric load and it has increased with the increase of electric load. The efficiency of the hydro turbine is the second variable that also changes the NPC significantly and the NPC decreases with the increase of hydropower as the

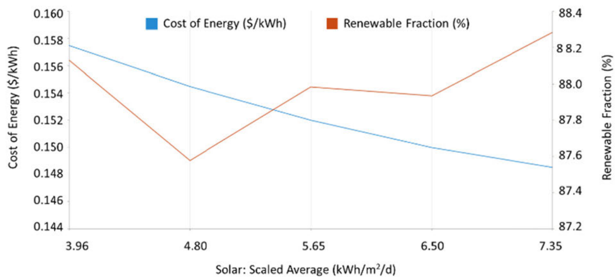


FIGURE 19. Variations of COE and renewable penetrations with the variations of solar irradiation.

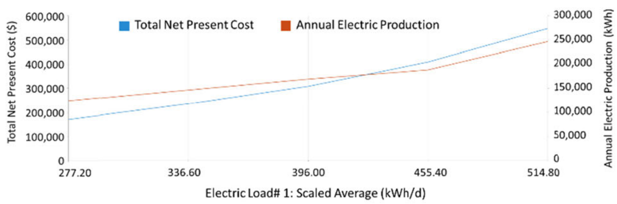


FIGURE 20. Variations of NPC and annual electricity production with the variations of electric load.

system can reduce dependency on other generating sources. NPC is also reduced with the increase in PV capital cost. Not a significant change in NPC is observed with the changes in the remaining five variables. Hence, this information will guide the designer/utilities to explore more with the key variables and prioritise technology to reduce uncertainty.

VI. DISCUSSIONS

The Zimbabwean government has recently introduced mechanisms for funding renewable energy-based system implementation program that encourages IPPs to invest in renewable energy applications in Zimbabwe. There will also be a fund established by the Ministry of Energy that will promote solar energy to address the electricity crisis. After the inception of a micro-hydro scheme at Chipendeke, the community has made significant improvements regarding its socio-economic development and it proved that this community can thrive when it has the resources. Therefore, government funding is essential to build an electrification scheme in the country's rural areas. Additionally, this feasibility study identified the techno-economic prospects of renewable energy-based system for Chipendeke community, which will guide the government, policymakers and utilities to identify the future initiatives to build the electricity sector to develop a sustainable future for the country.

A. SOCIO-ECONOMIC DEVELOPMENT

Implementation of the proposed hybrid system not only will support the current community demand but also could provide expansion opportunities for the health centre, allowing them to provide medical assistance to other villages. This renewable energy-based system also can supply power to the proposed welding and peanut butter making facilities; this could provide services and products, not only to the community but also to the surrounding cities and villages. In addition to this, the use of local artisans for the assembly, installation and maintenance of the system would result in

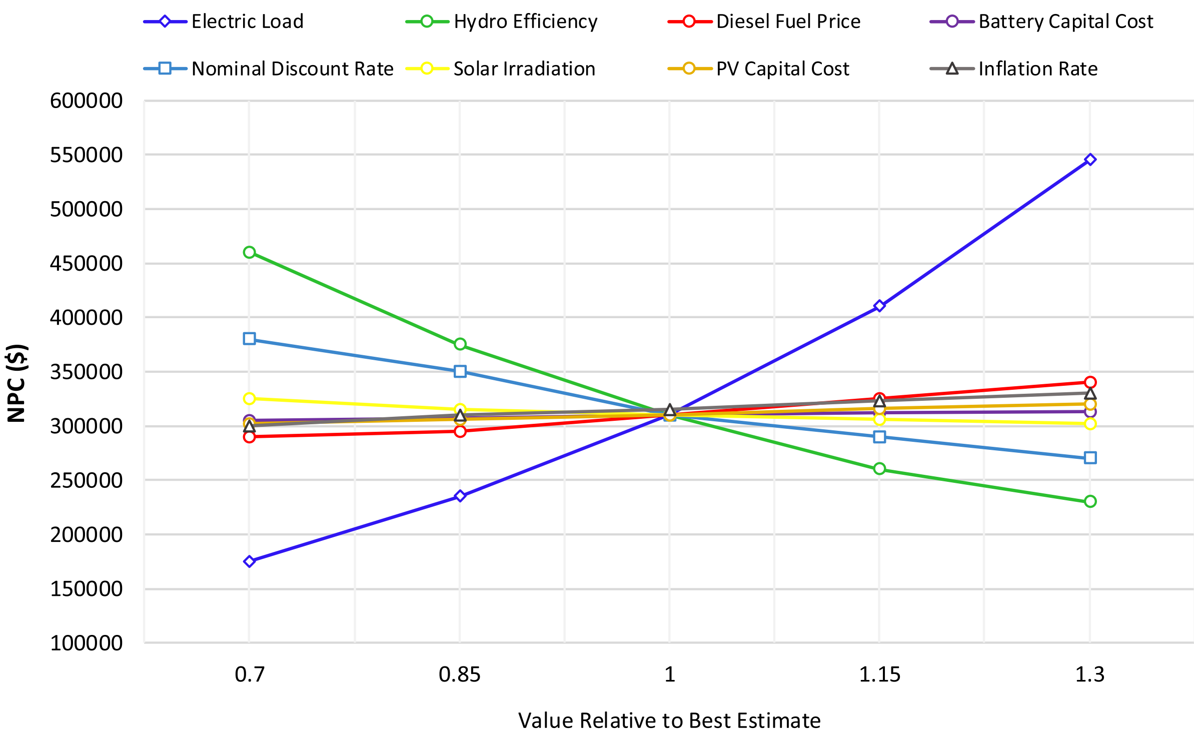


FIGURE 21. Effect of variations in the hybrid REPS with the variations of eight key variables.

job opportunities. All these opportunities would increase cash flow into the community, which may contribute to payments of the system's operational costs.

B. EDUCATION FOR FUTURE GENERATION

This facility will explore the possibility of an expansion in the educational sector, with the addition of a possible high school, which will increase the education rate of the community. In turn, this will produce an educated workforce for the future, which is the key to a country's development.

C. ENVIRONMENTAL IMPACT

As the community of Chipendeke currently relies on firewood for cooking, the implementation of this hybrid system would result in lower levels of deforestation. In addition to this, there would be health benefits, as the amount of smoke inhalation would be significantly reduced. With a renewable energy fraction of 87.5%, this system will be in line with the Zimbabwean government's goal to reduce carbon emissions by 33% by the year 2030, as well as meeting one of its renewable energy policy objectives of ensuring that rural areas have increased access to modern energy.

D. ELECTRICITY GENERATION

For this system, the main source of electricity will come from the micro-hydro system, followed by the PV, and then the diesel generator. The diesel generation will provide slightly more generation capacity than required because its minimum load ratio is 25%, to prevent it from operating at too low a load. It will also cater for the unexpected load demand or can be used during times of low PV output, periods of system maintenance or during faults. It will also complement the use of the hydro system during the rainy season, as there will be a low clearness index due to cloud cover, resulting in less power produced from the PV.

E. EXCESS ELECTRICITY GENERATION

When the hydro scheme was first implemented, water storage tanks were added to the system to heat water during times of excess electricity. As there is currently a generation deficit at the hydro system, these tanks are barely in use and as the optimum hybrid system will produce 16593 kWh/year of excess electricity, mainly from the excess power from the diesel generator because of its minimum load ratio, it is suggested that the storage tanks will act as dump loads for this excess electricity. This heated up water may be used for cooking, bathing and other requirements by the community. This excess electricity can also supply power to the community as it expands.

VII. CONCLUSION

The Zimbabwean government has established policies to tackle the energy deficit as well as to reduce the country's carbon footprint. By increasing and diversifying energy use options, integrating renewable energy into the energy mix including increasing investment in islanded energy systems in rural areas could implement the government's agenda. This study focused on an islanded power system that is already in operation in Zimbabwe, which has positive impacts on the community. Improvements were then suggested for this system, based on the energy needs of the community. This study developed a hybrid renewable energy-based stand-alone power system for the community of Chipendeke to evaluate the techno-economic and environmental potentialities. Including the existing hydro-only system, six case scenarios with many combinations were studied. From the analysis, it was seen that an off-grid hybrid Hydro/PV/DG/Battery system is the most optimum solution with a payback period of 2.33 year for the community. Of the analysed configurations, this system had the lowest NPC and COE of $307,657 and $0.165/kWh respectively and the highest RF of 87.5%. Amongst the considered eight sensitivity variables, it is found that electricity load changes the NPC more rapidly and increased with the increase of electric load.

The proposed system will increase future business expansion opportunities as well as improve the health care and education facilities, thus enhancing living standards and reducing global warming. The implementation of this system would be in line with the Zimbabwean government's objectives to ensure that rural areas have increased access to modern energy and can increase and diversify their energy options. This will not only play a part in reaching the government's target of reducing carbon emissions by 33% by 2030 but would also be contributing to the global initiative to achieve the UN SDGs, for a sustainable future for the country.

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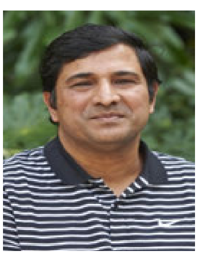

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